T-score of 0.12 indicates that added Gaussian noise does not significantly effect the results.

Spot-wobbling the scanning beam of a noisy picture increases the visible size of the noise which is analogous to lowering the frequency of the noise. It is a well known fact that low frequency noise is more detrimental to the quality of a television picture than high frequency noise. When the pictures were spot-wobbled without added noise, the PSE was 157 lines indicating a strong preference for the noninterlaced pictures in this case. When noise was added to the spot-wobbled pictures, there was an increase in the preference for the line-interlaced picture, PSE = 167 lines. This indicates that a combination of noise and spot-wobble is more detrimental to the quality of a noninterlaced picture than a line-interlaced picture by a significant amount. Interline flicker associated with the line-interlaced picture appears subjectively as noise to the observer. Could it be that the added noise in a spot-wobbled picture is partially confounded with the interline-flicker of the line-interlaced picture and therefore is not as visible as such as it is in the noninterlaced pictures?

Fig. 15 shows graphs of the preference percentile scores for the noninterlaced pictures over the interlaced picture for two levels of illumination summed over the additional variables. A significant difference was not detected for the change in illumination. Thus, one may conclude that a change in illumination will not change the subjective equivalency between line-interlaced and noninterlaced television pictures under the conditions of this experiment.

Fig. 16 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for the skilled observers and the nonskilled observer. The PSE for the skilled observers is a 166-line picture (Bi = 1.09) with a standard deviation of 21 lines. The PSE for the unskilled observers is a 163-line picture (Bi = 1.05) with a standard deviation of 21 lines. A T-score of 0.37 indicates there is no significant difference between the two groups of observers. However, an interesting significant difference was found within the skilled group of observers. The skilled observers were drawn from two television engineering groups at these laboratories which work more or less independently of each other. One group had a significantly stronger preference for the line-interlaced picture than the other. Yet when the data of the two groups were pooled the PSE of the skilled group and the PSE of the nonskilled group were not significantly different. This implies that when conducting subjective tests of this type where the results are applicable to a lay population, the possibility of a strong bias in a skilled group should not be overlooked.

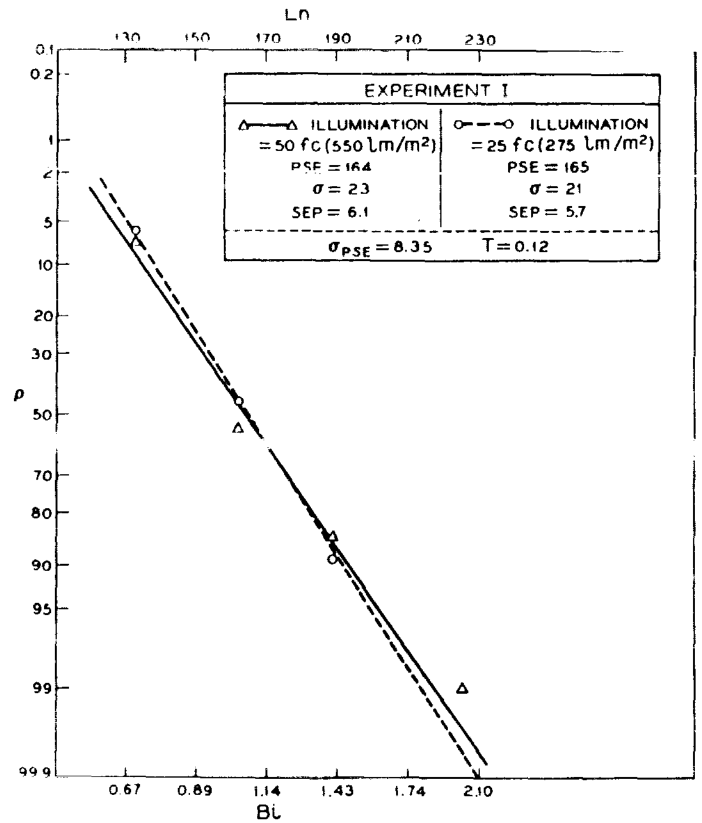

Fig. 15 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture at two levels of illumination. (Summed over other additional variables.)

Fig. 17 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for the blonde model is a 165-line picture (Bi = 1.08) with a standard deviation of 19 lines. The PSE of the brunette model is a 163-line picture (Bi = 1.05) with a standard deviation of 23 lines. Their T-score of 0.24 indicates there is no significant difference in their PSE's.

VI. EXPERIMENT II—EXPERIMENTAL DESIGN

The results obtained in experiment I indicate that the precision of estimation of the PSE could be improved by decreasing the step-size between the noninterlaced pictures. Accordingly, the ratio of the step-size in terms of number of lines between the noninterlaced pictures

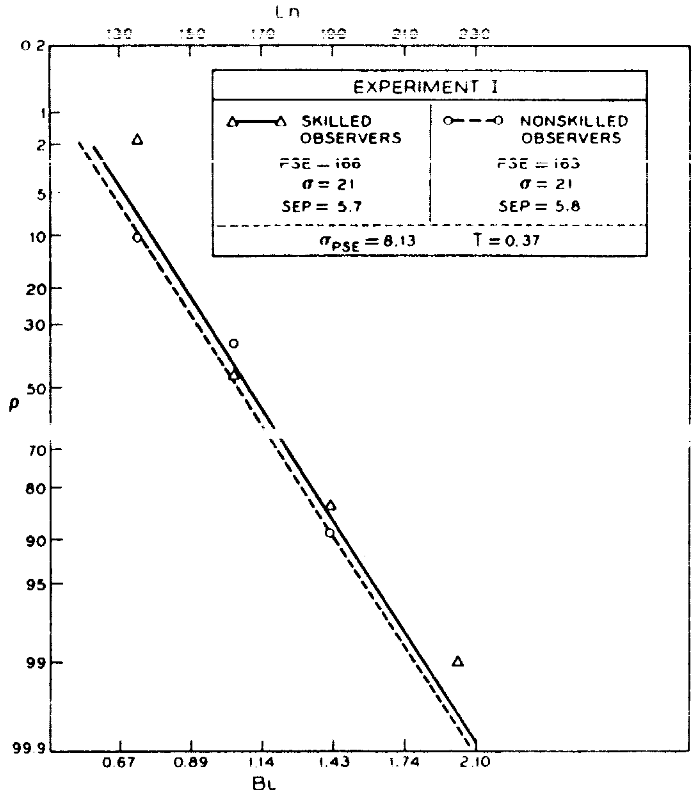

Fig. 16 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture for skilled and nonskilled observers. (Summed over all variables.)

was reduced to $\sqrt[9]{2}$ over the range of 135 lines to 189 lines. Table III shows these parameters and the values of the other parameters which were changed in order that the picture format would be consistent with the change in number of lines.

Another variable of importance, a change in picture luminance, was introduced at two levels in experiment II. These two levels were:

	Case I	Case II
High Light	80 fL (270 cd/m²)	50 fL (170 cd/m²)
Low Light	3.5 fL (12 cd/m²)	1.5 fL (5 cd/m²)
Contrast Ratio	23 : 1	33 : 1
Illumination	50 fc (550 lm/m²)	25 fc (275 lm/m²)

The ambient illumination was set at the two levels indicated in the table which the experimenter thought gave good picture rendition in

each case. It was felt that this was legitimate since experiment I indicated that a change in illumination did not significantly affect the PSE.

In addition to determining the PSE of the line-interlaced picture with respect to the set of noninterlaced pictures for the conditions cited above, it was desirable to determine the subjective relationship between the noninterlaced pictures. Accordingly, an incomplete factorial design was used where the line-interlaced picture was compared with each of the noninterlaced pictures and the adjacent (in terms of number of lines) noninterlaced pictures were compared with each other. A-B testing techniques were employed again. The order of A-B pairs and the order within A-B pairs was determined by random number tables.

The test apparatus described earlier was used except that it was modified to accommodate the new rates.

In case I, 12 nonskilled observers were used with two replications each. In case II, 9 nonskilled subjects were used with three replications each.

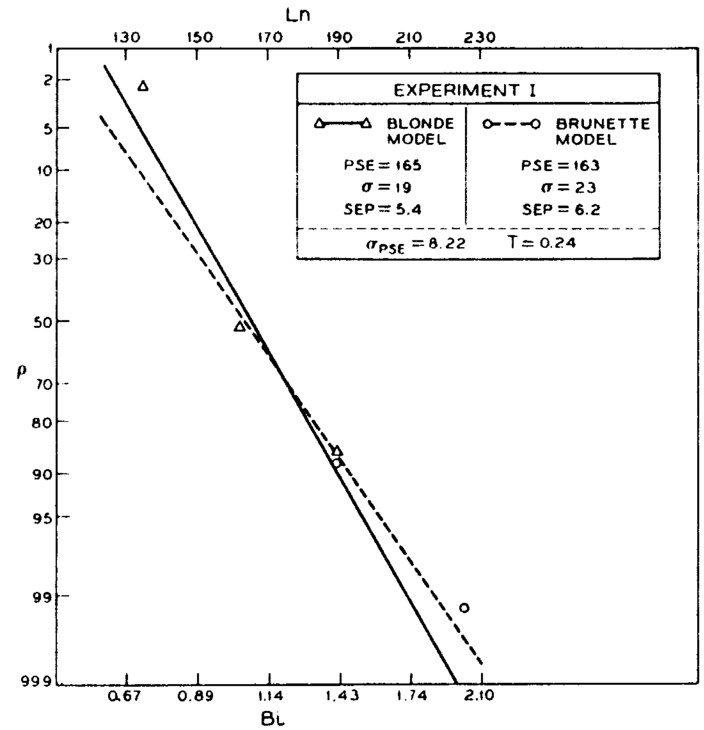

Fig. 17 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture for blonde and brunette models. (Summed over all variables.)

The test procedure and instructions to the observer were the same as those described in Section IV except for the necessary change in the number of "sets of pictures".

VII. EXPERIMENT II—RESULTS AND CONCLUSIONS

Each of the observers made a forced choice decision for one of the two pictures in each A-B pair presented to him. In addition to recording his preference, the time it took each observer to reach a decision was recorded for each A-B pair. It was assumed that time would vary

TABLE III—SOME PARAMETERS OF EXPERIMENTAL APPARATUS (EXPERIMENT II)

Number of lines	Line-interlace	Horizontal sweep rate (Hz)	Bandwidth (MHz)	Picture elements/frame	Visible picture elements/frame	Visible picture elements/line	Angular subtense between two lines at 40"
225	Yes	6750	0.575	38,333	28,366	142	2.2′
189	No	11,340	0.812	27,066	20,029	119	2.5′
175	No	10,500	0.695	23,166	17,143	110	2.7′
162	No	9720	0.575	19,166	14,183	102	2.9′
147	No	8820	0.495	16,500	12,210	92	3.2′
135	No	8100	0.415	13,766	10,186	85	3.4′

proportionately with the difficulty of reaching a decision, i.e., time would be well correlated with the first derivative of the percentile score.

Using time as the variable, control charts[10] were set up for the experiment. The control charts for the mean time indicated that the experimental apparatus was under control at all times. Range control charts indicated that all of the observers were within population control limits.

Table IV (a) lists the frequency of preference for the noninterlaced pictures over the 225-line interlaced picture for the two levels of luminance. Listed in Table IV (b) is the preference of the noninterlaced picture with the larger number lines over the adjacent noninterlaced picture with the lesser number of lines.

The data listed in Table IV (a) relating the interlaced picture to the noninterlaced pictures was converted to percentile scores and plotted on normal-probability paper as shown in Fig. 18.* Again assuming

* When the fifth data point is missing from the graph, it occurred at the 100th percentile for the 225-line noninterlaced picture.

TABLE IV — EXPERIMENT II

(a) Frequency of preference for noninterlaced pictures over 225-line interlaced picture

	Case	I	II
	No. of observers	12	9
	Replications	2	3
Number of lines (noninterlaced pictures)	189	22	24
	175	12	10
	162	7	2
	147	1	1
	135	2	0

(b) Noninterlaced pictures: frequency of preference for picture A over picture B in terms of number of lines

Case		I	II	Total out of 51 observations
No. of observers		12	9	
Replications		2	3	
Pix A	Pix B			
189	175	22	26	48
175	162	22	26	[illegible]
162	147	21	23	44
147	135	21	26	47

a normal distribution, a probit regression line was determined for each case. Chi-square tests indicated no conflict with the hypothesis of a normal distribution.

The data of experiment II was tested for significance in the same manner of experiment I.

For a high-light luminance of 50 fL (170 cd/m^2) the PSE was a 177-line noninterlaced picture ($Bi = 1.24$) with a σ of 12 lines and a SEP of 2.0 lines. For a high-light luminance of 80 fL (270 cd/m^2), the PSE was 171 line noninterlaced picture ($Bi = 1.16$) with a σ of 18 lines and a SEP of 2.6 lines.

In addition to the graphs of experiment II, Fig. 18 shows the graph of the results from experiment I (see Fig. 12) for a high-light luminance of about 100 fL (340 cd/m^2) summed over all variables. Thus, three values of high-light luminance are available in checking for a significant difference between high-light luminances.

The T-score for changes in high-light luminances of 50 fL (170 cd/m^2) to 80 fL (270 cd/m^2) and 80 fL (270 cd/m^2) to 100 fL (340 cd/m^2) is 1.83 and 1.44, respectively. These T-scores approach the significant value of 1.96. Thus, we may conclude that a change in high-light luminance of less than 30 fL (100 cd/m^2) over the range of 50 fL (170 cd/m^2) and 100 fL (340 cd/m^2) will not quite produce a significant difference in the PSE when comparing line-interlaced and

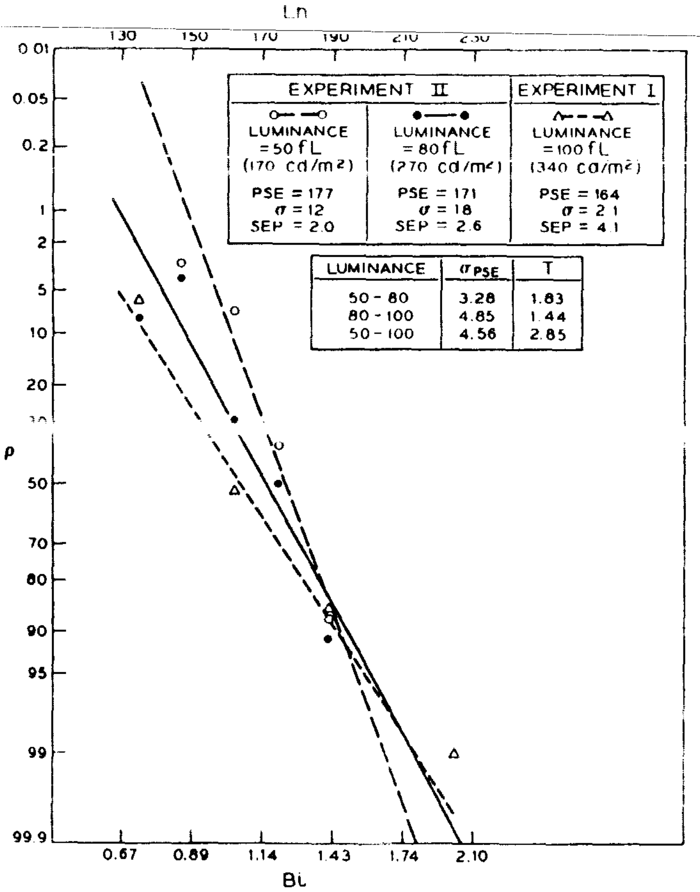

Fig. 18 — Experiment I and II—the preference for noninterlaced pictures over a 225-line interlaced picture for three levels of luminance.

noninterlaced television pictures under the conditions of these experiments.

The T-score for a change in high-light luminance of 50 fL (170 cd/m^2) to 100 fL (340 cd/m^2) is 2.85. This value of T is highly significant. We may conclude that a change in high-light luminance from 50 fL (170 cd/m^2) to 100 fL (340 cd/m^2) will produce a highly significant difference in the PSE when line-interlaced and noninterlaced television pictures are compared under the conditions of these experiments.

The preference of the noninterlaced picture with the larger number of lines over the adjacent noninterlaced picture with the lesser number of lines is not shown in graphic form. Table IV-B shows that about

90 percent of the observers preferred the pictures with the larger number of lines over the picture with the lesser number of lines. The exact meaning of these results is not obvious. Although the observers were asked to make their decisions on the basis of picture quality, we may instead have a measure of the observers ability to detect a difference in the number of lines between two pictures.* In other words, the observer in detecting which picture had the greater number of lines, may have assumed that this picture must also have the better quality. We may conclude that about 90 percent of the observers will be able to determine which of two noninterlaced television pictures has the greater number of lines when the ratio of the number of lines in the picture is $\sqrt[8]{2}$ over the range of 135-line pictures to 225-line pictures.

VIII. EXPERIMENT III—EXPERIMENTAL DESIGN

The fact that the image of a television picture is reproduced in lines on the picture tube screen is objectionable to most people. This is particularly true of low-resolution television systems with coarse line structures. Broadening of the scanning lines will aid in reducing the objectionable effects of the line structure. Asymmetrical defocussing of the scanning spot with a magnet attached to the neck of the picture tube is one of the most economical approaches to this problem though Monteath[11] has shown that it is not the best esthetic solution.

Asymmetrical spot defocussing was used in this experiment as described in Section II. The line-width to line-pitch ratio was set at approximately 1.7 for the interlaced picture and approximately 1.2 for the noninterlaced pictures.[6] Fig. 19 shows photographs of a line interlaced and noninterlaced picture with the line-width to line pitch ratios set for the preferred values.

The 225-line interlaced picture was compared with the five noninterlaced pictures described in Table III except that the 225-line noninterlaced picture described in Table I was exchanged for the 135-line noninterlaced picture of Table III.

Two levels of luminance and illumination were introduced as follows:

	Case I	Case II
High-Light	60 fL (200 cd/m²)	40 fL (140 cd/m²)
low-Light	3.5 fL (12 cd/m²)	1.5 fL (5 cd/m²)
Contrast Ratio	17.2 : 1	27.4 : 1
Illumination	100 fc (1100 lm/m²)	50 fc (550 lm/m²)

* The experimenter found that the change in the number of lines (about 9 percent) was quite evident in each case, whereas the change in bandwidth (about 18 percent) was difficult to detect. Baldwin,[8] found that a change in bandwidth of 16 percent was not perceptible in his experiments.

Fig. 19 — Experiment III—photographs of asymmetrically defocussed pictures. (a) 225-line interlaced picture, (b) 225-line noninterlaced picture.

On the assumption that a change in illumination did not have a significant effect on the PSE, the illumination was changed to give good picture rendition with the levels of luminance used.

The order of presentation of A-B pairs for each case and the order within pairs was determined by random number tables.

In case I, 16 nonskilled observers were used with 3 replications each. In case II, 15 nonskilled observers were used with 3 replications each.

The test procedure and instructions to the observers were the same as those described in Section IV except for the necessary change in the "number of sets of pictures."

IX. EXPERIMENT III— RESULTS AND CONCLUSIONS

Each of the observers made a forced choice decision for one of the two pictures in each A-B pair presented to him. In addition to recording his preference, the time it took each observer to reach a decision was recorded for each A-B pair.

Using time as the variable, control charts[10] were set up for the experiment. The control charts for the mean time indicated that the experiment was under control at all times. Range control charts indicated that all of the observers were within population control limits.

Table V lists the frequency of preference of the noninterlaced pictures over the 225-line interlaced picture for the two cases under test.

The data listed in Table V was converted to percentile scores and plotted on normal-probability paper as shown in Fig. 20. Assuming a normal distribution, a probit regression line was determined for each case. Chi-square tests indicated no conflict with the hypothesis of a normal distribution.

For case I with a high-light luminance of 60 fL (200 cd/m^2) the PSE was a 173-line picture (Bi = 1.18) with a σ of 22 lines and a SEP of 2.1 lines. For Case II with a high-light luminance of 40 fL (140 cd/m^2) the PSE was a 186-line noninterlace picture (Bi = 1.37) with a σ of 19 lines and a SEP of 2.3 lines. The value of the quantity T was 3.75 indicating a significant difference between the two PSE's.

We may conclude that when the line-width to line-pitch ratio is set at its preferred value for interlaced and noninterlaced television

Table V — Experiment III: Frequency of Preference for Noninterlaced Pictures over 225-Line Interlaced Picture when the Line-Width to Line-Pitch Ratio is 1.7 for Interlaced Pictures and 1.2 for Noninterlaced Pictures

	Case	I	II
	No. of observers	16	15
	Replications	3	3
Number of lines (noninterlaced pictures)	225	47	45
	189	45	25
	175	28	10
	162	13	4
	147	9	3

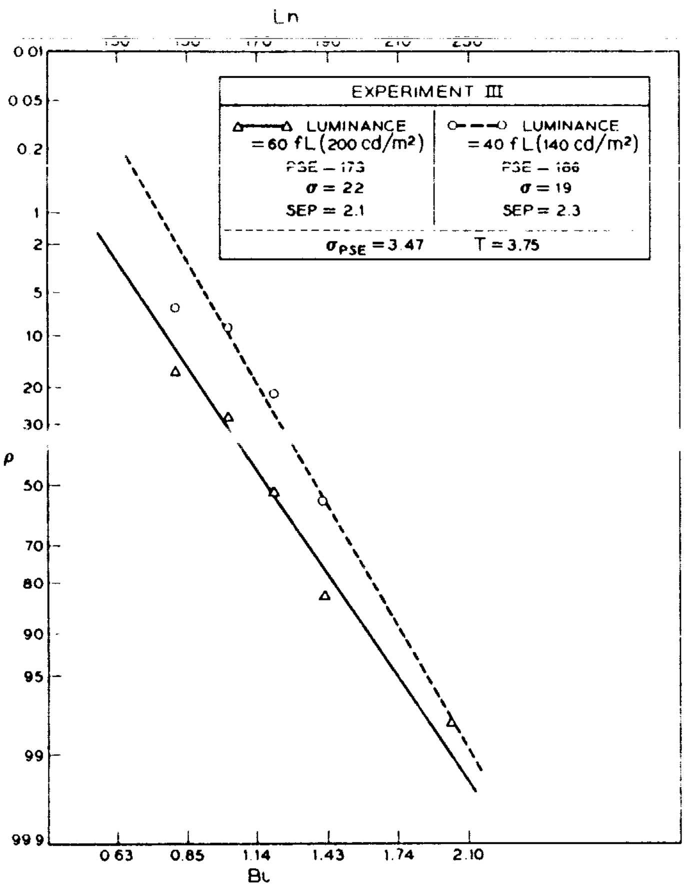

Fig. 20 — Experiment III—the preference for noninterlaced pictures over a 225-line interlaced picture for two levels of high-light luminance with the line-width to line-pitch ratio set to its preferred value.

pictures there will be a significant difference in the PSE when the high-light luminance is changed from 60 fL (200 cd/m²) to 40 fL (140 cd/m²) or vice versa under the conditions of this experiment.

X. SUMMARY AND CONCLUSIONS

It has been found that the line interlacing of low-resolution television pictures provide the observer with substantially less than a 2 : 1 savings in bandwidth under the conditions of these experiments. In the most optimistic case where the high-light luminance was 40 fL (140 cd/m²) and in which the line-width to line-pitch had been optimized the subjective bandwidth savings was about 37 percent.

It was found that high-light luminance had a significant effect on the subjective equivalence between line-interlaced and noninterlaced television pictures. In the worst case with a high-light luminance of 100 fL (340 cd/m²) the line-interlacing of a 225-line television picture provided a savings in subjective bandwidth of about 6 precent. Under similar test conditions at a high-light luminance of 50 fL (170 cd/m²), the subjective bandwidth savings was about 24 percent.

The main effects of the variables added Gaussian noise, spot-wobble illumination, two types of models, and two types of observers did not produce a significant difference in their results. The first-order interaction between each of these variables with the exception of noise and spot-wobble was not significant.

A significant first-order interaction was found between added Gaussian noise and a sinusoidally spot-wobbled scanning beam. When the scanning beam of the test pictures was spot-wobbled with a 7.14-MHz sine wave, the 225-line interlaced picture did not provide any subjective savings in bandwidth. However, when noise with a Gaussian distribution was added to the spot-wobbled picture the subjective bandwidth savings was about 10 precent. This indicates that added noise is more detrimental to the quality of a spot-wobbled noninterlaced picture than to a spot-wobbled line-interlaced picture.

It was found that about 90 percent of the observers preferred the noninterlaced picture with the greater number of lines when the ratio of the number of lines of the two pictures was $\sqrt[8]{2}$ and the vertical resolution in each picture was approximately equal to the horizontal resolution.

The same amount of picture information is presented in both the 225-line interlaced picture and the 225-line noninterlaced picture. The noninterlaced picture is a quiet picture in which the small details may be easily detected and tracked by the observer. This same detail is visible in the interlaced picture, but the observer must look "through" the interline flicker effects and resist the intrinsic desire of the eye to track stroboscopic patterns in order to see the detail. It is highly probable that the results of this experiment would have been quite different if the observers task was to recognize and identify fine detail, such as the recognition and identification of alphanumerical material.

In the design of a low-resolution television system the choice between line-interlace and noninterlace is not completely resolved by these experiments. These experiments provide us with a long awaited measure of the subjective equivalence between line-interlaced and noninterlaced television pictures under the conditions described. Before a final decision is made many other factors such as cost of implementation, the subjective effects of PCM processing, repeater spacing, the subjective effects of crosstalk, etc. if applicable, must be considered. Finally, although the full benefits of a 2 : 1 savings in bandwidth is not realized by line-interlacing it does provide some bandwidth savings in all of the cases studied except one and furthermore, line-interlacing appears to partially mask the affects of added noise.

XI. ACKNOWLEDGMENTS

Most of the members of the Visual Systems Research Department of Bell Laboratories have made some contribution to this experiment. W. T. Wintringham has directed and assisted this experiment from its beginning. J. A. Murphy and F. C. Bollwage designed and built the display terminal. Consultations with P. D. Bricker, M. W. Baldwin, Jr., C. C. Cutler, B. Prasada, and H. Levitt were most helpful in the design and analysis of the experiment.

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Low-Resolution TV: Subjective Effects of Noise Added to a Signal

By R. C. BRAINARD

(Manuscript received September 19, 1966)

The visibility of noise in a television presentation is related to the spatial-frequency and flicker-frequency components of the noise display. The visibility of sine wave interference, which generates a sine wave grating on a TV screen, demonstrates remarkable linearity by giving a good approximation to the visibility function measured with narrow bands of noise.

A difference in visibility between moving and stationary gratings produces a difference between noise visibility in TV and photographs. This fact is important in evaluating the computer simulation of a system by calculations for a single TV frame. The variation of visibility with motion predicts increased visibility for additive noise in a television frame repeating system. Applications to predistortion and reconstruction filters for transmission of analog and digital TV signals are discussed.

I. INTRODUCTION

For the design of a television communication channel it is desirable to have a figure of merit for comparison of channels. As our sophistication in the design of communication channels increases, so we must also increase our sophistication in defining and measuring a suitable figure of merit. As a measure of merit we may use the power spectrum $N(\omega)$ of the error, or noise, added in the channel which can be measured for all frequencies, ω, in a given transmission system. However, the ultimate receiver is a person viewing the picture, and his sensitivity to noise superimposed on the picture depends upon the distribution with frequency of that noise. This dependence of the viewer's sensitivity to noise can be considered equivalent to a linear filter and a linear detector. We will call this sensitivity function a subjective noise-weighting function, $W(\omega)$, defined on the video bandwidth, 0 to Ω.[1,2,3,4] This subjective noise-weighting function gives the value at each frequency of the relative contribution of noise to an overall figure of merit. We define this figure of merit as $1/P$, where

A Video Compression Efficiency Analysis using Progressive and Interlaced Scanning

Eric Petajan

AT&T Bell Laboratories
Murray Hill, NJ 07974

Introduction

The delivery of video programming to the consumer at a reasonable cost and with the highest picture quality depends on a variety of technologies and systems. Individual scenes are transduced with video cameras, film cameras followed by telecine, or reduced by computer. The video signals are then stored on analog video tape or digitized and stored on tape, disk, or electronic image buffer. A finished program is produced by editing individual scenes together. For the last 50 years programs have been delivered to the consumer using the NTSC system. Consumer grade video tape has more recently provided a program delivery alternative to broadcasting. Today we are on the verge of introducing motion compensated video compression into the program delivery process. The consequences of this are far reaching and affect the traditional economics of the entire process. In particular, the choice of video scanning format affects the cost and quality of the video compression to varying degrees depending on scene content. This paper provides an analysis of the relationship between scanning format, scene content, and video compression efficiency as it affects picture quality.

Source Material Preparation

In the interest of conserving computing time and storage, a frame size of 704 H x 480 V was chosen. The 60 frame per second progressive scenes were derived from progressive high definition source material which was appropriately filtered and resampled to 704H x 480V The interlaced scenes were than derived from the progressive scenes by selecting the odd lines from the odd progressive frames and the even lines from the even progressive frames. Of course, the interlaced scenes have an effective vertical resolution which is significantly lower than the progressive scenes[1].

Video Coder Configuration

A software implementation of an MPEG-2 coder[2] was used with progressive refreshing (see below). No B-frames (bidirectional prediction) were used since the benefit of B-frames is independent of scanning format. A bit-rate of 4 Megabits/sec was chosen for all experiments, except for the coding of random noise because of its difficulty. The refresh rate was selected to achieve a startup in one third of a second for both formats. Field/frame coding was used for all interlaced scenes. Figure 1 illustrates how the encoder can select whether to construct a given block of pixels from an interlaced frame or from two fields.

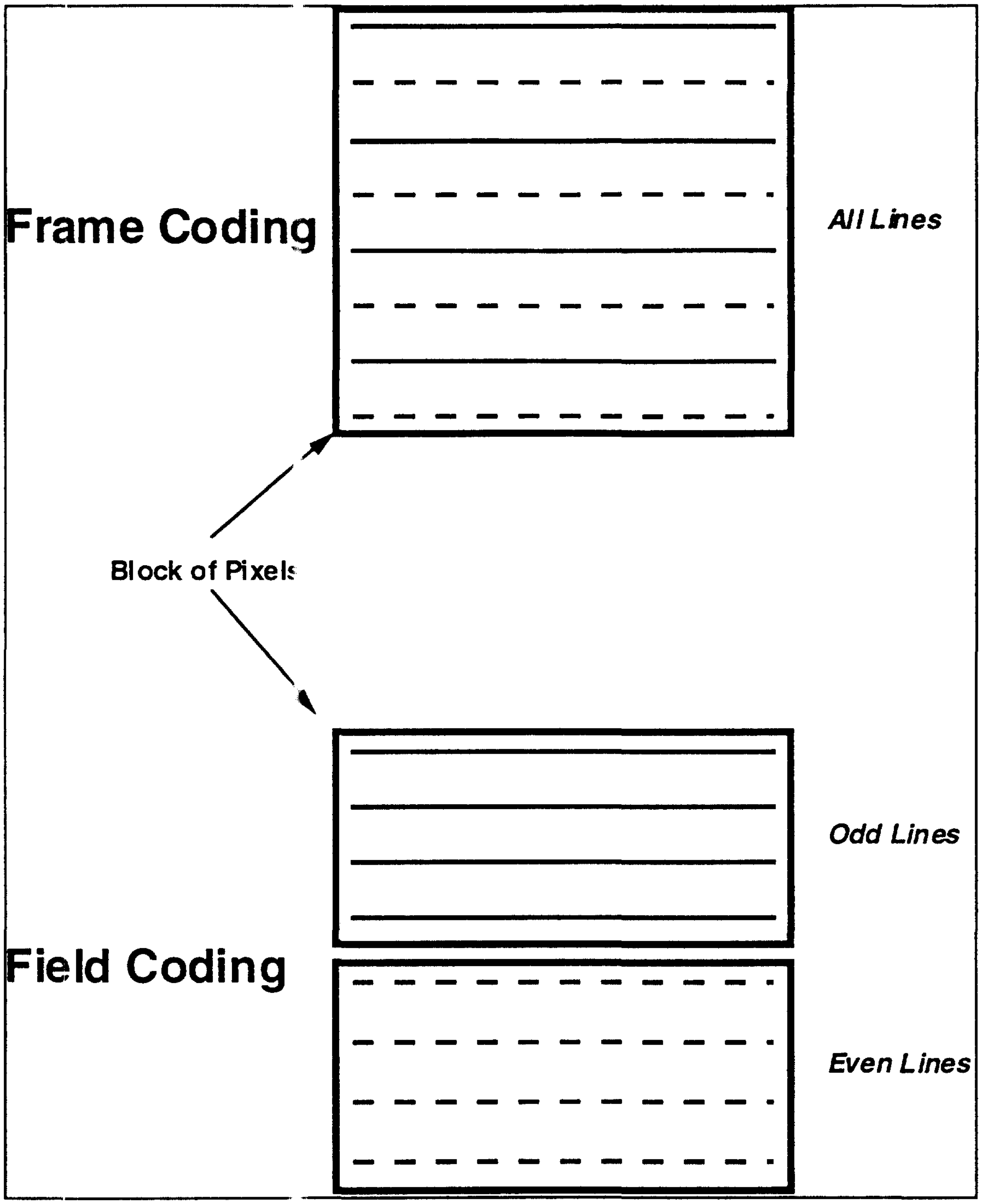

Figure 1. Field/frame coding

The picture quality was measured using the mean squared error of the difference between the coded and the original pictures. This was expressed as a signal to noise ratio in decibels using the following equation:

$$SNR = 10 \log_{10} [255^2/(MSE(\text{coded picture})]$$

It is generally accepted that differences in SNR of less than .5 dB are not significant.

Static and Predictable Scenes

Motion compensated transform coding explicitly measures spatial and temporal redundancy in an image sequence and only sends unique picture information to the decoder (see Figure 2). The use of intra-frame-only coding (refreshing shown in Figure 3) for decoder startup (channel acquisition), or to provide insert edit points, is an exception to temporal redundancy removal in the encoding process and requires an increase in coded bit-rate to maintain equivalent picture quality. The best illustration of this is in the coding of a static image sequence (repeated still). Virtually the only information required by the decoder after startup is a set of zero-length motion vectors for each frame which consumes a tiny fraction of the bit-rate for a motion sequence. However, the use of I-frames or I-blocks (I means intra-frame coding) dramatically increases the bit-rate to levels comparable to coded motion scenes.

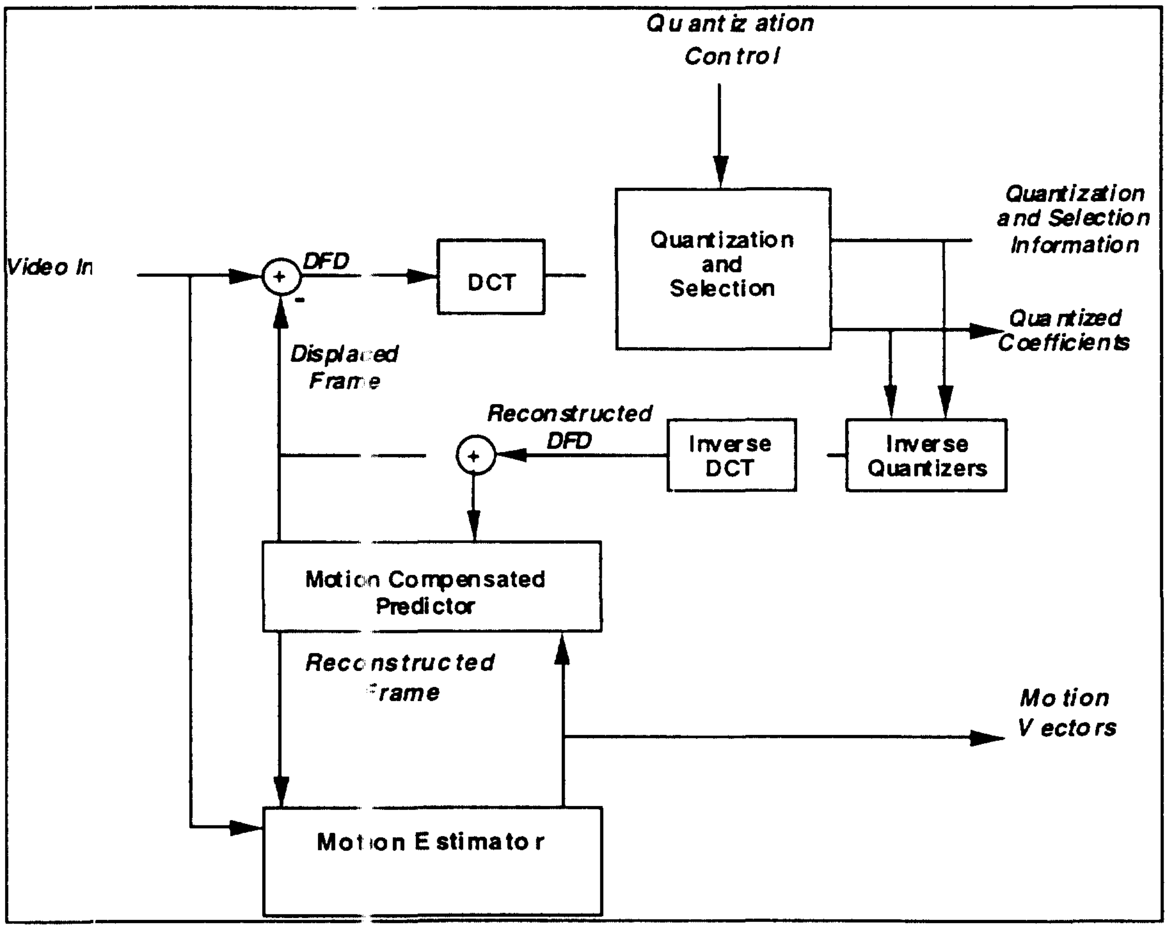

Figure 2. Video Encoder Loop

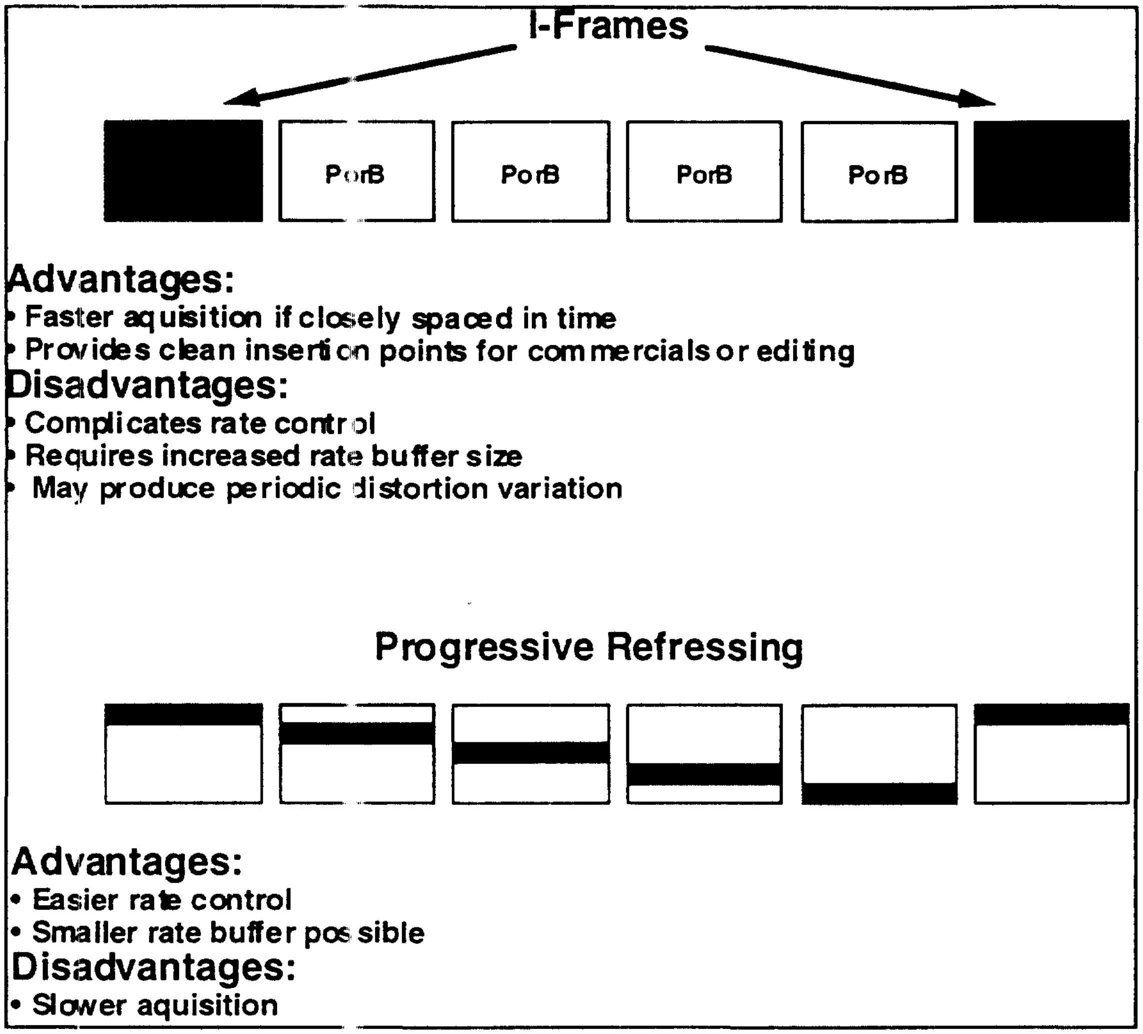

Figure 3. Refreshing techniques

To achieve a given decoder startup time or insert edit point period, an entire frame must be intra-frame coded within the given time constraint. Since the frame rate in our progressive format (60 frames/sec) is twice that of the interlaced format (30 frames/sec), the ratio of intra-code frames to inter-coded frames must be twice as high for the interlaced format compared to the progressive format to achieve the same decoder startup time. Therefore, the number of intra-coded frames per second is equivalent between our interlaced and progressive formats. This holds true for both I-frames and progressive refreshing with I-blocks. Since virtually all of the bit-rate from a coded static scene is consumed by intra-frame information, the coded picture quality should not depend on whether interlace or progressive scanning is used. However, the coding process will not remove interlace artifacts. Thus, for static scenes, progressive scanning provides equivalent coded picture quality compared to interlaced scanning without interlace artifacts. This was verified experimentally and the results are shown in the first row of Table 1. The image of Chicago was coded with an SNR of 39.83 dB using progressive and 39.97 dB using interlaced scanning. This .14 dB difference is not significant.

Scene	Bit-rate	Progressive SNR(dB)	Interlaced SNR(dB)	Prog SNR - Int SNR
Chicago Still	4 Mbits/sec	39.83	39.97	-0.14
Panned Map	4 Mbits/sec	21.92	21.84	0.08
Noise	12 Mbits/sec	18.10	19.57	-1.47
Chicago Zoom	4 Mbits/sec	27.19	26.91	0.28
Mall	4 Mbits/sec	34.61	34.96	-0.35
Traffic	4 Mbits/sec	39.40	38.58	0.82

Table 1. Video coding results

The second row of Table 1 shows results for a Panned Map which is highly predictable and contains no noise. As expected, the two formats performed nearly equally with the progressive SNR higher than the interlaced SNR by .08 dB.

Random Noise

Now consider the coding of a sequence of frames of random noise. This type of scene is the opposite of a static scene from a video coding perspective, i.e., static scenes are completely correlated (at least temporally) and noise is completely uncorrelated. The only opportunity for redundancy removal in this case is the substitution of coding artifacts for some of the random noise using human perceptual modeling. Again, the intra-coded block rate is equivalent between our two formats but now the inter-coded blocks consume nearly as many bits as the intra-coded blocks and the interlaced format has half as many inter-coded blocks per second as the progressive format. Therefore, the coding of interlaced random noise should provide better fidelity than progressive random noise. In effect, interlaced scanning of random noise discards half of the noise samples before coding which reduces the bit-rate proportionately. The third row of Table 1 shows the experimental results for this case where the coding of a noise sequence produced a 1.5 dB increase in SNR using interlace compared to progressive scanning. A bit-rate of 12 Megabits/sec was used for this difficult scene to give reasonable SNR values.

Typical Scenes

Row 4 of Table 1 shows coding results for a scene which contains no noise but is only partially predictable because it is a computer generated zoom using the Chicago still. Block-based motion compensation can only approximate non-translational motion such as zooming or rotation. Progressive scanning is slightly favored for this scene with a .28 dB increase in SNR compared to interlace.

Typical camera scenes contain some noise (electronic or film grain), static or temporally predictable areas (panning), and areas with unpredictable or complex motion (uncovered background, fast zooms). The contribution to the total coded bit-rate from each type of scene content is proportional to the area of each type integrated over the duration of the scene. The contribution to coded bit-rate from noise is proportional to the noise amplitude and spectral characteristics. Table 1 lists two scenes in rows 5 and 6 which were filmed at 30 frames/second called Mall and Traffic. These scenes were scanned and digitized before coding and they were doubled in speed to 60 frames per second in order to derive both 60 frames/sec progressive and 30 frames/sec interlace from the same scenes. Of course changing the frame rate in simulation is done merely by changing a software parameter. The Mall scene was shot indoors and contains the random motion of a fountain and some complex motion (people walking). Increased film grain from indoor light levels and random motion gives the interlaced form of this scene a .35 dB increase in SNR compared to the progressive form. This is not significant and does not result in any visible improvement in picture quality. The Traffic scene was shot outdoors and contains various speeds of motion. The progressive form of this scene produced a .82 dB increase in SNR compared to the interlaced form. This is a somewhat visible difference in picture quality. The interlaced forms of both scenes contain visible interlace artifacts.

Conclusions

The experimental results clearly show on a wide variety of scenes that the picture quality of coded progressive scenes is equal or better than that of the interlaced form of the same scenes. In one case the progressive picture quality was significantly better than interlaced (not considering interlace artifacts). This may have been due to the increase in spatial frequency energy in moving areas. If frame coding is used, moving edges are jagged leading to high frequency DCT coefficient amplitude. If field coding is used, the smaller block size reduces the efficiency of the DCT.

Since the pixel rate of the progressive format is twice that of the interlaced format, the coding efficiency for progressive scanning has been shown to be twice that of interlaced scanning. The only exception to this is scenes with high amplitude random noise. Properly coding such scenes calls for noise filtering before coding using progressive scanning. If the noise was intentionally added for effect then a block-based pseudo-random noise pattern should provide sufficient spatial and temporal redundancy for good picture quality. If the availability of progressive scan cameras is in question then deinterlacing before video coding should provide most of the benefit of progressive scanning.

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Abstract :

The Scanning Formats extension of the HAMLET project finds its source in the Recommendation on Scanning Formats formulated by the RACE Image Communication Project Line (January 1994). The purpose of this deliverable is to re-analyze the considerations presented in this recommendation, to raise new elements – technological improvements, new considered services, simulation results – and to try to evaluate the fallbacks of the studies on progressive and interlaced coding efficiency.

Keywords :

Scanning Formats, Progressive, Interlace, Image capture, Scanning Artefacts, Signal Processing, Deinterlacing, Reinterlacing, Filtering, Multi-resolution, Scalability, Slow-motion, Chroma-keying, Aspect Ratio, Frame Rate, Still Picture, Multimedia, Coding Efficiency, Display.

Summary

Progressive scanning is the most direct approach to represent two-dimensional images. However, in the early years of television, an interlaced format was chosen in order to efficiently save bandwidth. Even if this latter format introduces some well known artefacts such as *interline twitter*, *line crawling* and *field aliasing*, these effects were not so annoying at the time of early television, mainly due to the limited spatial definition and the limited brightness range of the cameras and the displays at that time. Today, with the progress in technology, these artefacts become more obvious. However it is still true without any reasonable doubt that for analog television interlaced scanning offers an improved picture quality compared to progressive scanning at the same transmission bandwidth. This does not necessarily hold for digital television because the picture quality depends on the coding efficiency at a given bit rate. In such a context, the advent of the future digital and/or high-definition television may be seen as a good opportunity to bring a change in scanning formats. Even if the use of a progressive format could require at first sight twice the bandwidth of the interlaced one, the increase in vertical and temporal correlations within and between frames provides a significant improvement in the coding efficiency. Also, even if an interlaced scheme is chosen for the future digital television, a progressive format may still be of interest as an intermediate format in order to improve the coding of interlaced sequences. Advantages and drawbacks of interlaced and progressive scannings are reported in this deliverable.

Contents

Advantages and Drawbacks of Interlaced and Progressive Scanning Formats

1 Introduction

Interlaced and progressive scanning formats often have been the center of intense discussions about their respective advantages and drawbacks, especially in the context of making a choice for the future digital television. Chosing one or the other format basically reverts to the problematic choice between an ingenious bandwidth reduction (yet offering satisfying quality for the end-user) and an improved visual quality at the display. Signal processing theory tells us that halving the information rate, which is the case when the interlaced format is chosen instead of the progressive one, must reduce the quality of the displayed picture and so the saving in bandwidth is accompanied by a variety of effects like *line crawling* and *interline twitter* [1]. However interlaced format has been chosen in the early years of television considering it was one of the most interesting solution to achieve data compression with regard to the available technology. It also offered a clever trade-off between image data compression and display quality. Today, the improved quality of the sources and displays make the viewer much less tolerant of the defects of the interlaced format, especially for large displays (e.g. peripheral vision), at close viewing distance and high brightness levels. The change from analog to digital television may be seen as a good opportunity to change formats. Hopefully, since most digital communication services are new, the backward compatibility constraints in the choice of a scanning format are still limited. This choice however needs to be made with much care, to avoid backward and lateral compatibility problems that would become difficult to solve in the future [2]. In addition, in order to leave space for future upgrades throughout all the video coding chain it could be envisaged as a wise step not to degrade image quality at the very beginning of the process, i.e. inside the camera, choosing a lossy scanning format. But even if an interlaced scheme is still chosen for future developments, a progressive format may be still of interest as an intermediate format for improving the coding efficiency and simplify image processing.

This deliverable will discuss advantages and drawbacks of interlaced and progressive formats considering multiple viewpoints. The following section (section 2) will be devoted to the historical reasons which led to the choice of interlaced format for the early television. We then will discuss the influence of the scanning format on the visual perception of the displayed image (section 3). Next sections are structured following the logical order of blocks inside a typical video broadcasting chain (figure 1), from the signal generation to the final displaying, and involves camera technology (section 4), signal processing aspects (section 5), coding performances (section 6) and display technology (section 7). Finally, last section (section 8) will describe some scenarios for the introduction of a progressive scanning format in television.

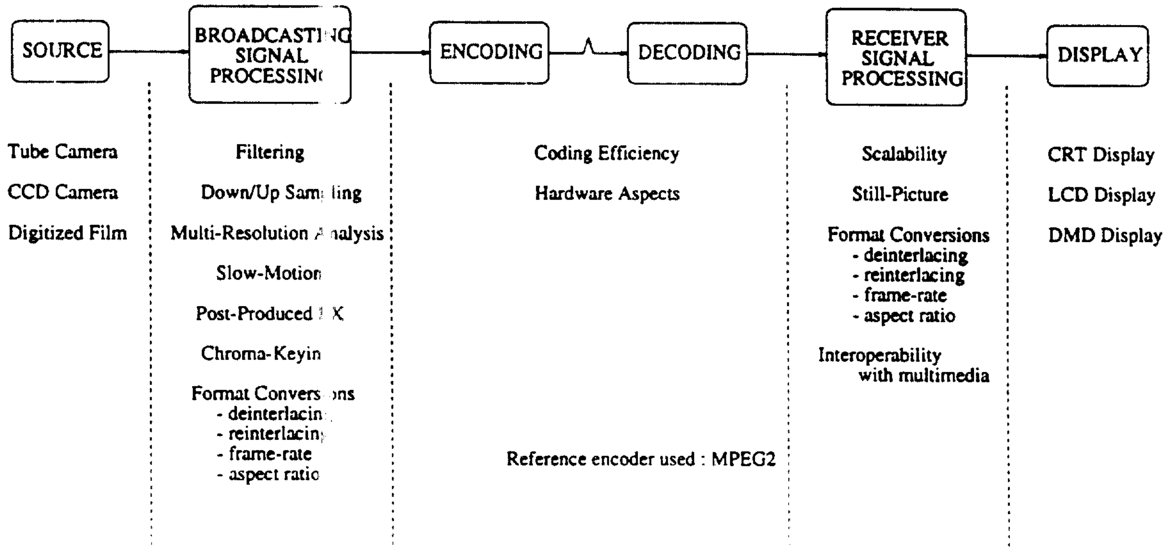

Figure 1: Video broadcast main blocks and aspects directly related

2 Historical Considerations

2.1 The Choice of an Interlaced Format

The choice of the actual television system arose from numerous compromises between the visual quality of the displayed image, the bandwidth required for the transmission, the technical feasibility of the fundamental components (analysis tube, cathodic ray tube, etc.), the cost price of the receiving set and other economic considerations.

At the time of early television, a 50Hz field frequency was chosen considering principally the following points [3]:

1. *Correct movement restoration.* Image frequency (or frame frequency) must be larger than 15 images/second in order to avoid a jerky effect in fast motions.
2. *Display tube.* Cathodic ray tubes have exponential decreasing brightness response. The light emitted from a portion of the screen is pulsed, leading to some flickering effect. In usual working conditions of screen size and brightness, field flickering disappears for frequencies above 50Hz. By means of interlacing, the *mean lightening* emitted from a portion of the screen is pulsed at field frequency. Consequently, *field frequency* must be at least equal to 50Hz.
3. *Device conception.* An economic realization of the receiver involves some restrictions to the field frequency in order to avoid visible defects due to the influence of

the 50Hz-alternative mains onto the display process. Hum effect may influence polarization voltages and lead to some interference with the luminance signal. Also, magnetic radiation issued from the feeding transformer may influence the cathodic beam and alter the geometry of the displayed picture. These defects are much less perceptible when they appear static on the screen. It implies that they have to be synchronized with the display frequency.

These considerations led to the choice of a 50Hz field frequency (60Hz for countries for which a 60Hz mains was adopted).

About the format itself interlaced was mainly chosen for limiting the bandwidth required to transmit a television channel : interlacing can be seen as a subsampling process capable to reduce the bandwidth by a factor of two (figure 2) without limiting the vertical resolution in static pictures. Interlaced format also allows to make hardware implementation easier (e.g. deflection control at the Cathodic Ray Tube - CRT) and consequently lower the price of consumer's television set.

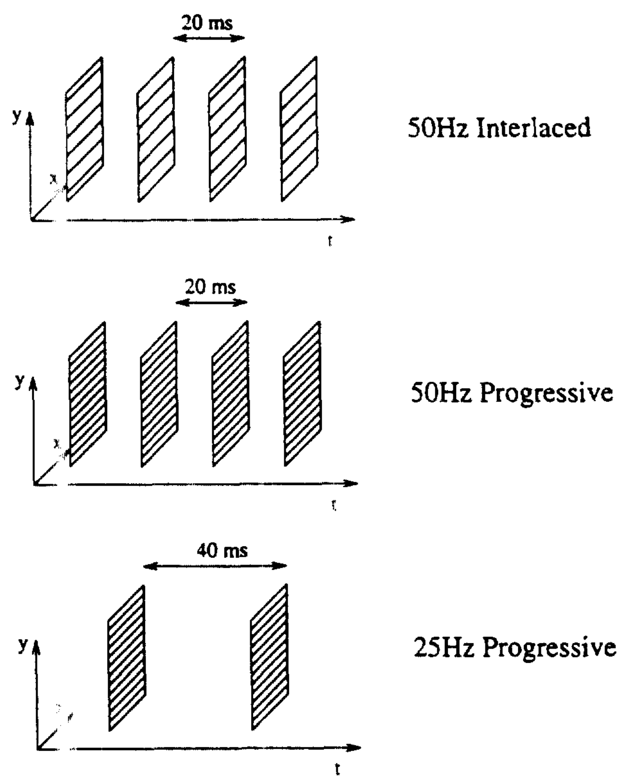

Figure 2: The different scanning formats

Unfortunately, interlacing produces some specific defects like *interline flicker*, *line crawling* and *pairing*. These defects will be further described in section 3.

2.2 About a 25Hz-progressive Format

In order to avoid the above mentioned defects, let us notice that a 25Hz-progressive format might have been chosen at the time of the early television instead of the interlaced format. Twenty-five frames a second are high enough for a very large class of picture material, including all films. However, each frame has to be repeated in order to convert the display refresh into a 50Hz refresh rate and so avoid large area flickering. This technique works fine and is commonly used to screen films (24Hz-progressive) on cinema, broadcasting films on television or even as an intermediate format within particular television cameras [4]. 25Hz-Progressive format requires the same bandwidth as interlaced but does not suffer from the interlaced defects. However, this format was not chosen at the start of early television. First, because frame memories needed to perform the frame repetition were nearly non-existent at that time (and certainly too expensive to be integrated in every receiver). But also because the deflection processing at the display must be twice as fast as for interlaced, resulting again in increasing the cost price of the receiver. At last, let us notice that repeating twice the same image may lead to some annoying jerk effect in moving parts of the scene at critical velocities. In order to avoid this, the integration time of the camera must be equal to the elapsed time between two successive images : 40ms for 25Hz-progressive instead of 20ms in the case of 50Hz-interlaced/progressive. Consequently, 25Hz-Progressive sequences suffer from increased blur in quick moving parts of the scene.

3 Visual Considerations

3.1 Scanning Artefacts

The "analog" scene captured by a television camera may be seen as a function depending on three variables : the time, the horizontal and the vertical directions. In order to convert this function into a one dimensional electric signal, it is required to sample (at least) two of these parameters. Therefore, the time variable and the vertical dimension have been sampled (figure 2). The resulting video signal provides signal at fixed moments and fixed lines. This "scene"-scanning process generates some defects which might be visible under some conditions :

1. *Line structure visibility.* Caused by the vertical sampling and increased by close viewing.
2. *Jerk in motion.* Appears when the temporal sampling frequency is too low (below 15 images/second).
3. *Large area flicker.* It depends more on the CRT refresh (pulsed excitation and exponential decreasing brightness response) rather than the choice of the temporal sampling frequency itself. However, they are related. This large area flickering effect is increased for high brightness values and for peripheral vision (increased flicker-sensitivity of the eye).

3.2 Additional Artefacts of Interlaced Format

The above mentioned defects of the scanning process stands for progressive format as well as for interlaced. In addition, interlaced format suffers from further defects. These are [1, 3, 6]:

1. *Interline flicker.* When lines are enough spaced to be distinguished by the eye (large displays or close viewing distance), alternating fields causes the twittering of the line structure. Also, if an object has a sharp horizontal edge, it will be present in one field but not in the next. The refresh rate of the edge will be reduced to the frame rate, 25Hz (or 30Hz) and will become visible as twitter.
2. *Line crawling.* Whilst the vertical resolution of a test card is maintained with interlaced, apart from the twitter noted, the ability of an interlaced standard to deal with motion is halved. Line crawling is caused by the halving of the vertical resolution for slowly moving parts of the picture in the vertical direction. It also causes diagonal moving edges to be crenelated.
3. *Pairing.* Interlacing is correct when the lines resulting of the merged fields are strictly equally spaced. For different reasons, it could not be the case at the display. It may thus bring some lines nearer causing larger black intervals to appear. This *pairing* effect increases the line structure visibility and damage the image quality.

These effects may also be explained in the light of the sampling theory [5, 6]. In a frequency domain, sampling reverts to repeat the spectrum of the "analog" scene at harmonics of the field repetition and the line repetition rates (figure 3). In order to avoid aliasing (i.e. overlapping of the different repeated spectra) a pre-sampling filtering must be performed at the camera.

Temporal pre-filtering is only due to the remanence effect in the camera tube. The choice of this parameter is not obvious because various applications have to be considered: from very slowly moving pictures to scenes with very quick motion. Those filtering effects are poor.

The vertical spatial pre-filtering is obtained by defocusing the camera optics or the electron beam (i.e. modifying the analysis spot size). The spot acts as an integrator of the luminance over a finite region. Once again, the performances of such system are poor. For digital television, were horizontal direction has also to be sampled, templates for horizontal pre-filtering filters were optimized by the CCIR and EBU.

The scanning defects visible at the display are caused by the presence of the repeated spectra (dotted lines in figure 3). In order to reduce it, some post-filtering must be performed. Most of this post-filtering count upon the properties of the human vision. The human eye may be compared to a spatio-temporal low-pass filter. Although there is no separability between space and time, the behavior of the eye may be assimilated to a 50Hz-cutoff frequency low-pass temporal filter and a spatial low-pass filter with a cutoff frequency of approximately 25 cycles by degree of visual angle (e.g. 250 cycles/screen

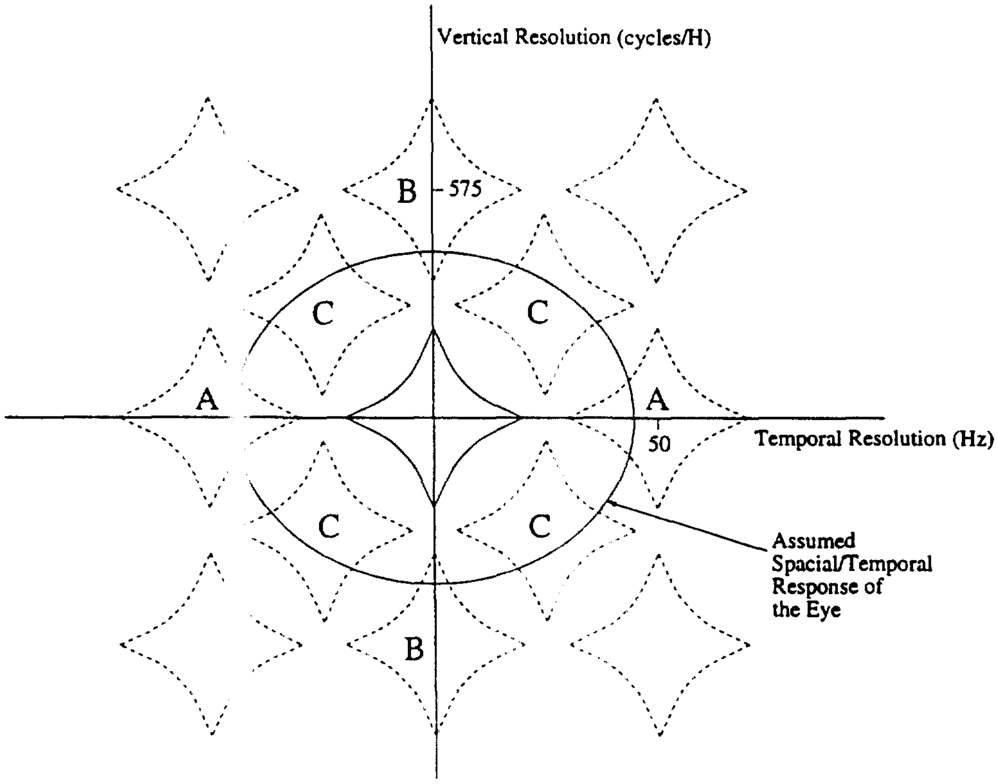

Figure 3: Repe ition of the spectra for interlaced scan (25Hz/575 lines)

height for a viewing dis ance of 6H or 350 cycles/H at 4H). This is also shown in figure 3.

The spectra repeated a , the multiple of the field frequency are responsible for the large area flicker (particular y the spectra labeled A). Some post-filtering is obtained from the tube remanence an l the temporal low-pass filtering effect of the eye.

The repeated spectra a ong the vertical frequency axis are responsible of the line structure visibility (particu arly the spectra labeled B). As no vertical low-pass filtering is used for the display, tl e only way to eliminate that effect is to take advantage of low-pass property of the h ıman eye and the finite size of the picture tube spot. In order to have the wanted ey low-pass effect, the observer has to stay far enough from the screen. The line struct ıre is generally dimensioned for a viewing distance of six times the height of the scree

As shown in figure 3, he interlaced scanned format has also spectra located at quincunx points (labeled C). Those spectra are responsible for the interline flicker and the crenelated diagonal m ving edges.

3.3 Kell factor

These same spectra are also responsible for the introduction of a so named *Kell factor*. A vertical sampling frequency of 575 lines per screen height theoretically allows to display vertical spatial frequencies up to 287.5 cycles per screen height. However, extending the vertical bandwidth up to this limit leads to an additional flicker due to the aliased spectra as illustrated in figure 4.

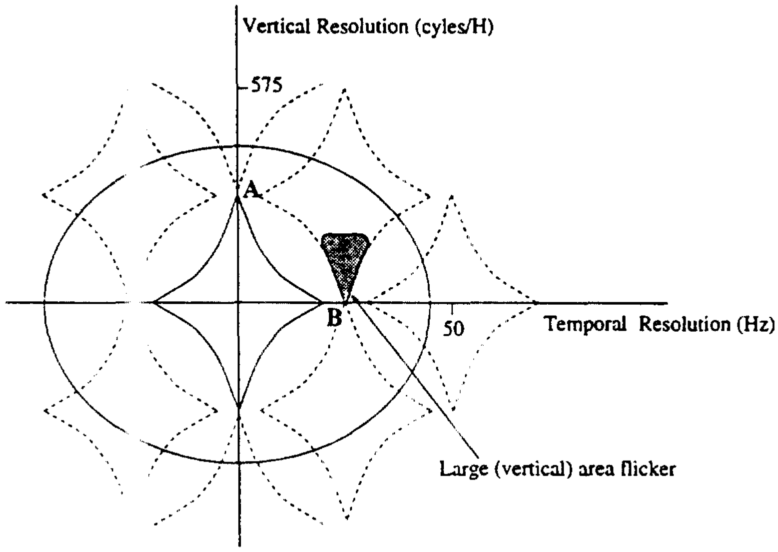

Figure 4: 25Hz flickering (Interlaced 50Hz/575 lines)

The effect of this repeated spectra, in particular the effect of the flicker area represented in figure 4, can easily be explained. At first, let us notice the relationship that exists between the points labeled A anb B in this same figure. Point labeled A represents a static (i.e. temporal frequency equals zero) television sequence which contains the highest possible vertical definition. On the opposite side, the point labeled B only has a poor vertical definition but owns the maximum allowed temporal resolution. The television sequences associated to these "spectral points" are illustrated in figure 5. This figure shows that, when these two sequences are displayed in the interlaced format, they give rise to the same displayed sequence and the viewer is not able anymore to determine which was the original scanned sequence. It is the definition itself of the aliasing phenomenon. In this case, it produces an additional flicker.

This flicker has a low vertical frequency, which means it affects large (vertical) areas, and has a temporal frequency close to 25Hz which reveals to be annoying. In order to minimize this effect, some additional pre-filtering has to be performed, reducing the vertical resolution below its theoretical limit. This reduction factor is called the *Kell factor* (figure 6) and has a typical value of 0.7 (but may vary up to 0.9 or 1 if no filtering is processed). This filtering is achieved at the camera.

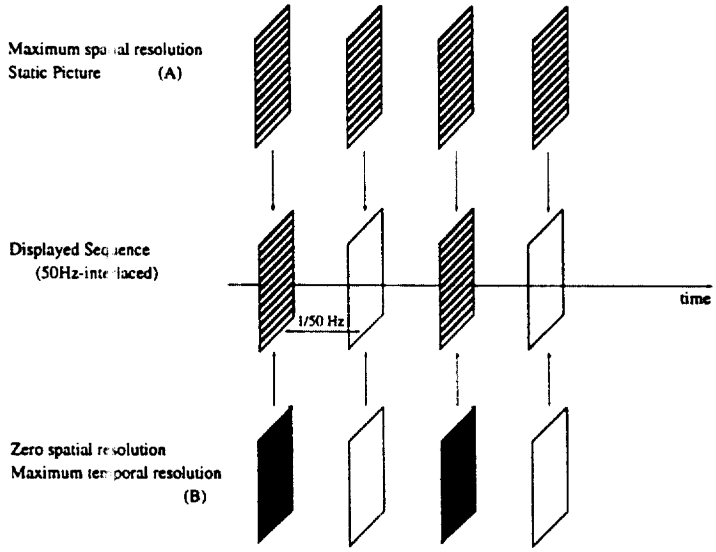

Figure 5: Aliasing phenomenon (50Hz-interlaced)

3.4 Progressive format

Compared to interlace, progressive scanning offers the benefits of a improved vertical resolution, especially on moving parts of the picture for which intra field aliasing is avoided. As illustrated in figure 7, progressive scanned sources do not suffer from inter-line flicker or crenelated moving edges (label C on figure 3). Also, they do not require additional vertical filtering like mentioned for the Kell factor.

3.5 Subjective Comparison between Progressive and Interlaced formats

Tests have shown that all other things being equal (screen size and total number of lines per screen height) a 2:1 interlaced picture has to be viewed from almost twice as far away as a progressive scan picture [1]. It was also shown that for the same viewing distance, progressive scan needs about 35% fewer lines compared to interlaced in order to offer the same vertical resolution [7].

4 Source Image Capture Aspects

The influence of source image capture devices reflects throughout all the video broadcasting chain and also on the choice of the scanning format. The substantial SNR loss incurred in progressive scanning compared to interlaced in pickup tube camera technology has practically determined the concentration of all the researches on the interlaced format. However, the introduction of the HDTV together with the fast growing of the CCD technology seems to modify this scenario. In fact, while researches on conventional interlaced cameras mainly focus on upgrades regarding lower weight, dimensions, cost,

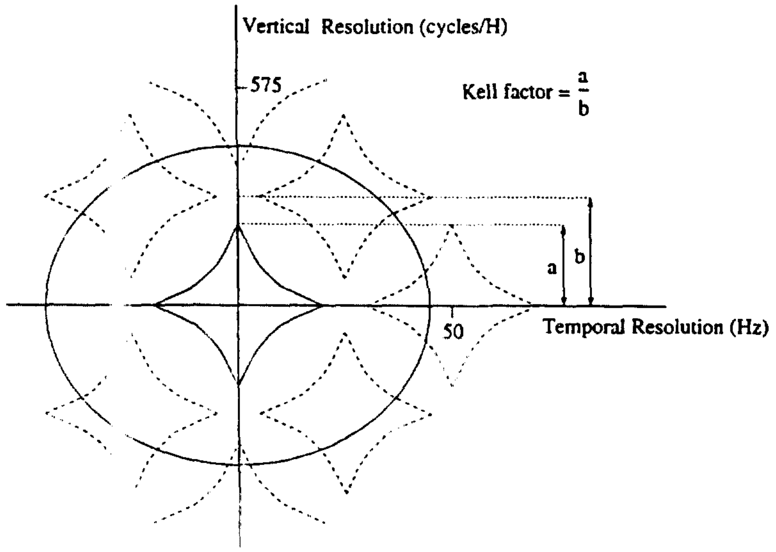

Figure 6: Kell factor (Interlaced 50Hz/575 lines)

target voltage, and easier control (for important parameters such as the temporal aperture), requirements of HDTV lead to improve the performances of the CCD technology. These progresses can thus be used to reduce the performance gap in sensitivity and SNR between interlaced and progressive scan. In the following some of the latest contributions in this domain are briefly synthesized.

SNR evaluation for a video-camera passes through a study of noise sources, physically related to the characteristics of image capture and of the generation of the output current/voltage signal. There are basically two kinds of noise sources in a TV camera [8] : the first one is *quantum noise* (or *shot noise*), related to the photoelectric converter present in a tube pickup and in the photo diodes of CCD; its power spectrum is flat both for tube and for CCD cameras. The second one is *device noise* (or *triangular noise*), which for tube is mainly due to the first stage amplifier noise, and it increases in proportion to the cube of the signal bandwidth. The latter is 9 dB lower with interlaced than with progressive scanning [10]. It explains the poor quality of sequences taken through a classical progressive tube camera, as well as the low contrast and brightness observed in these pictures.

More difficult is an efficient computing of SNR for a CCD camera, because of the presence of various device noise sources (*reset noise*, *amplifier noise*, *shot noise* of the dark current), with specific frequency behavior and without a clear dominance of a single component. In addition it is noticeable that CCD chips usually performs interlaced scanning by summing the signal charge of two vertically adjacent pels, alternating the combinations of the two pels by the field, so the signal voltage (and sensitivity) in the progressive operation is half the interlaced one. By summing up the increase/decrease of noise power contributions and taking into account the last consideration, the SNR determined by device noise of a progressive CCD camera decreases by $(6+\alpha)$ compared to that of an interlaced one, where $-3 < \alpha < +3$ expresses the variable dominance of one noise over the others and depends on the manufacturing technology. Moreover,